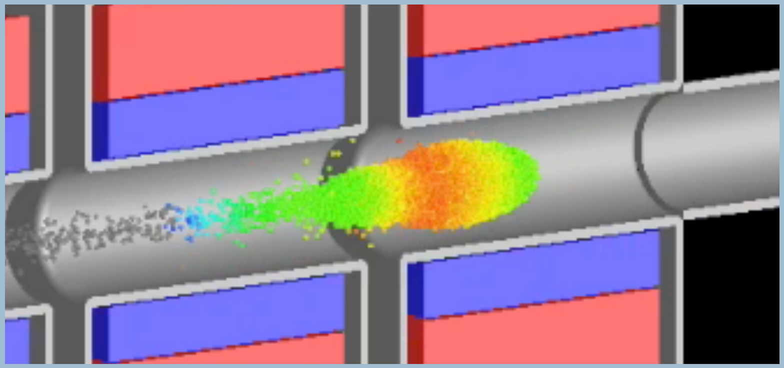
LLNL-PRES-611535

Overview of NDCX-II capabilities: the ion beam



Beam traversing an acceleration gap

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West Coast High-Energy-Density Science Collaboration Workshop

LBNL and SLAC

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The Heavy Ion Fusion Science Virtual National Laboratory

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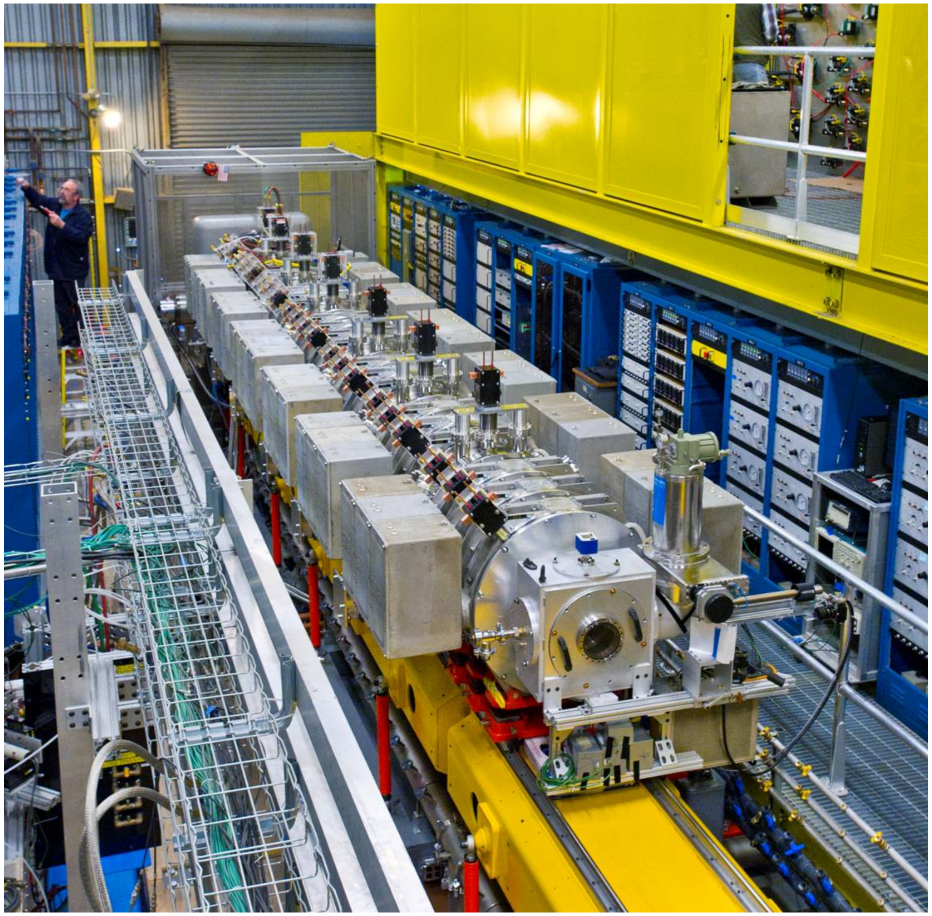
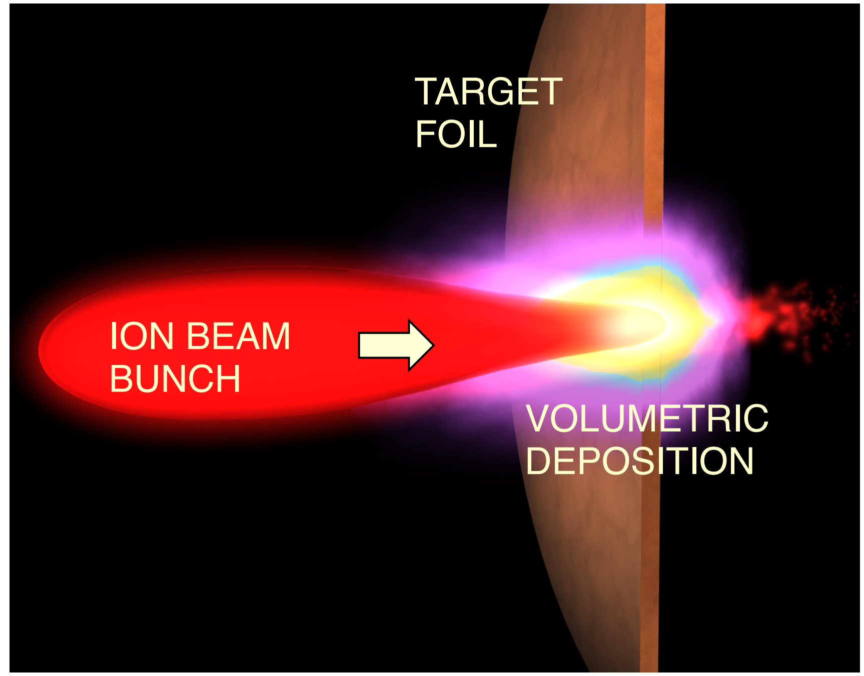
Neutralized Drift Compression Experiment-II (NDCX-II)





A new user facility for studies of:

- warm dense matter physics
- heavy-ion-driven target physics
- space-charge-dominated beams

The NDCX-II ion beam will be unique

Ideal performance of "mature" system:

Machine Characteristics:

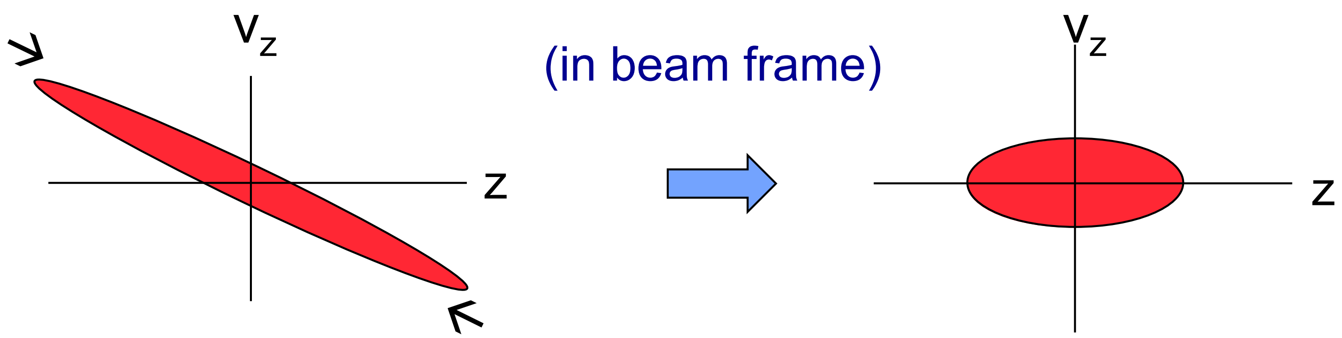
- 130 kV, ~ 600 ns Li^+ injector
- 12 induction plus 15 drift cells
- 2-3 T beam-transport solenoids
- Neutralizing plasma drift section for final compression
- 8.5 – 9 T Final Focus Solenoid
- Intercepting & non-intercepting beam diagnostics
- Target chamber & instrumentation
- 2 shots/minute repetition rate

	NDCX-I	NDCX-II 27-cell (design goals)
Ion species	K^+ (A=39)	**Li^+ (A=7)**
Total charge	15 nC	**50 nC**
Ion kinetic energy	0.3 MeV	**1.2 MeV**
Focal radius (contains 50% of beam)	2 mm	**0.6 mm**
Bunch duration (FWHM)	2 ns	**0.6 ns**
Peak current	3 A	**36 A**
Peak fluence (time integrated)	0.03 J/cm^2	**8.6 J/cm^2**
Fluence w/in 0.1 mm diameter spot	0.03 J/cm^2 (50 ns window)	**5.3 J/cm^2 (0.6 ns window)**
Fluence w/in 50% focal radius & FWHM duration	0.014 J/cm^2	**1.0 J/cm^2**

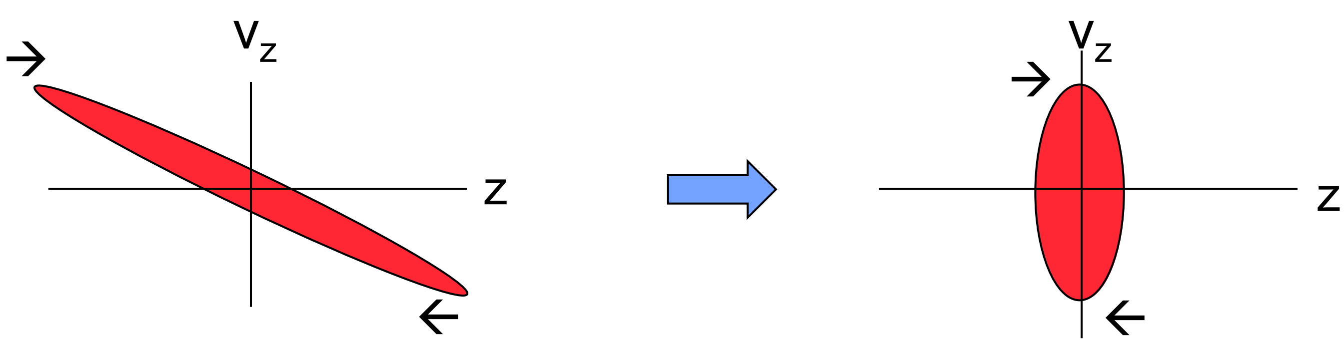
The "drift compression" process is used to shorten an ion bunch

- Induction cells impart a head-to-tail velocity gradient ("tilt") to the beam
- The beam shortens as it "drifts" down the beam line

- In non-neutral drift compression, the space charge force opposes ("stagnates") the inward flow, leading to a nearly mono-energetic compressed pulse:



- In neutralized drift compression, the space charge force is eliminated, resulting in a shorter pulse but a larger velocity spread:



NDCX-II applies drift compression to its ion beam *twice*

Initial non-neutral pre-bunching leads to a dense non-neutral beam in the accelerator

Final neutralized drift compression onto the target

inject → apply tilt → drift → accelerate → apply tilt → neutral-ized drift → target

NDCX-II will compress a 1 m, 600 ns initial bunch to ~ 6 mm, 1 ns at the target.

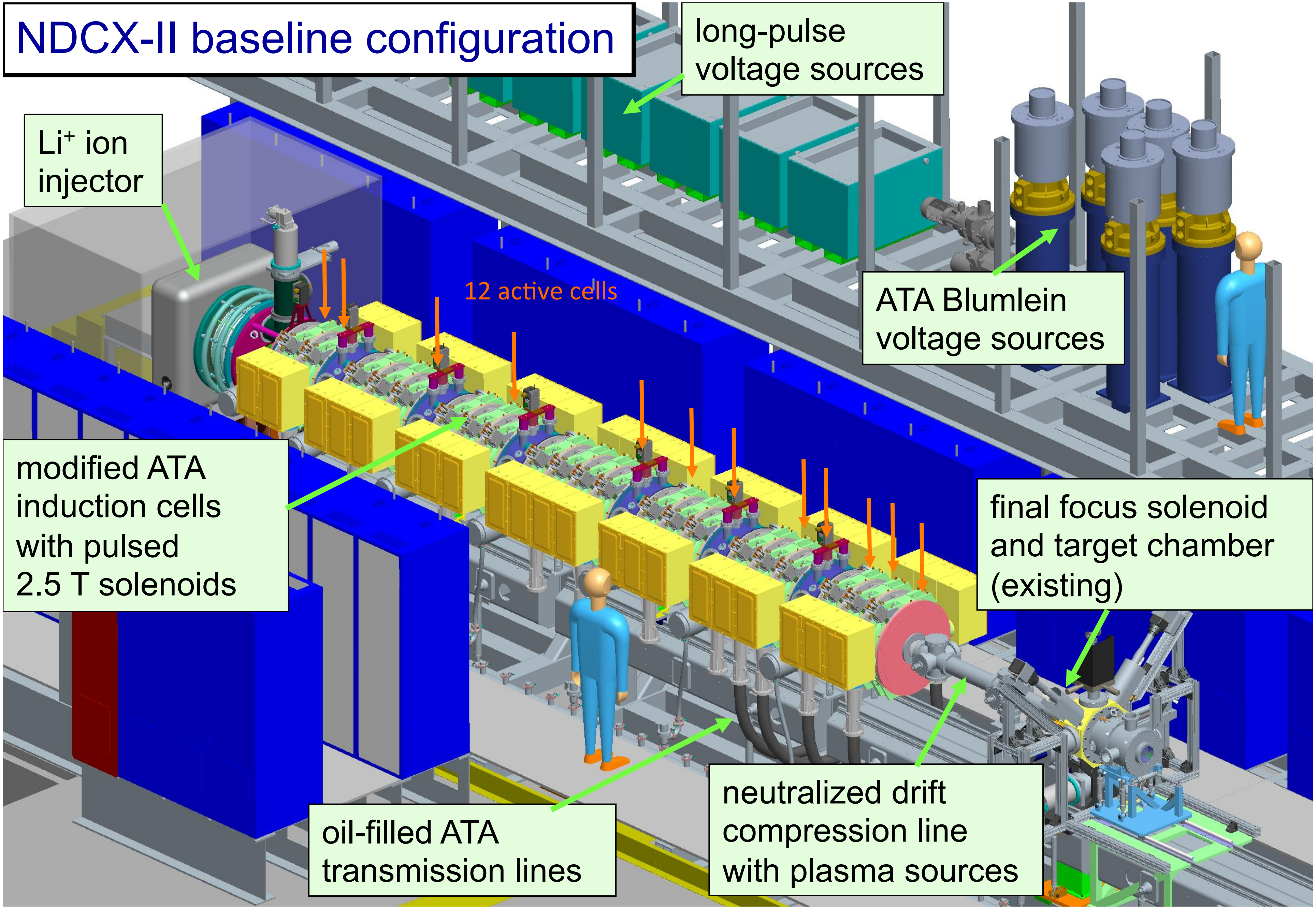
"Perveance" is space charge potential energy / beam kinetic energy:

$$K = \frac{2q\lambda}{4\pi\varepsilon_0 m v^2}$$

- Almost all beams have modest K; *e.g.*, the GSI linac has K ~ 4×10^{-6}.
- HIF driver beams will have K's of 10^{-4} - 10^{-3}.
- NDCX-II has a peak K of 10^{-2}

We will study this compressed beam - a stringent test of understanding

NDCX-II baseline configuration



Detail showing last induction cell and neutralized drift line

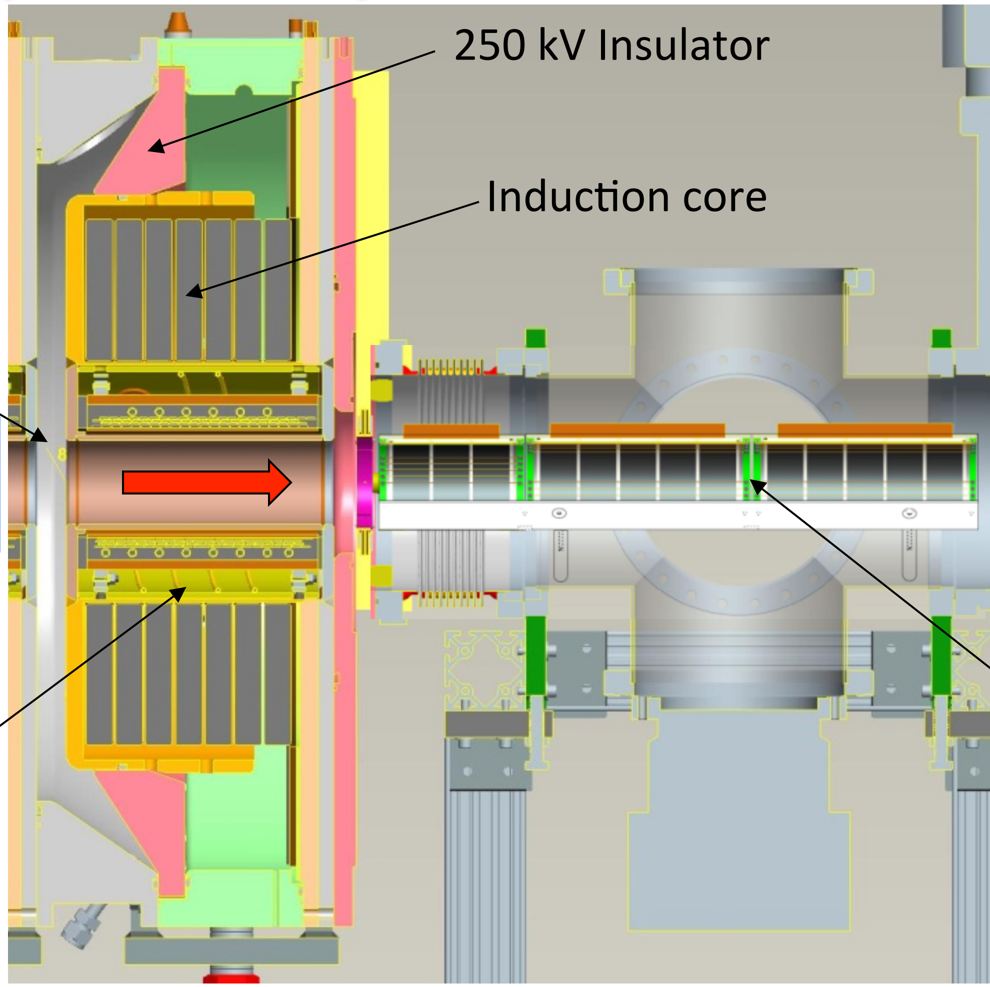
Final induction cell

Accelerating voltage (EMF) appears across this gap

250 kV Insulator

Induction core

Main NDCX-II Linac

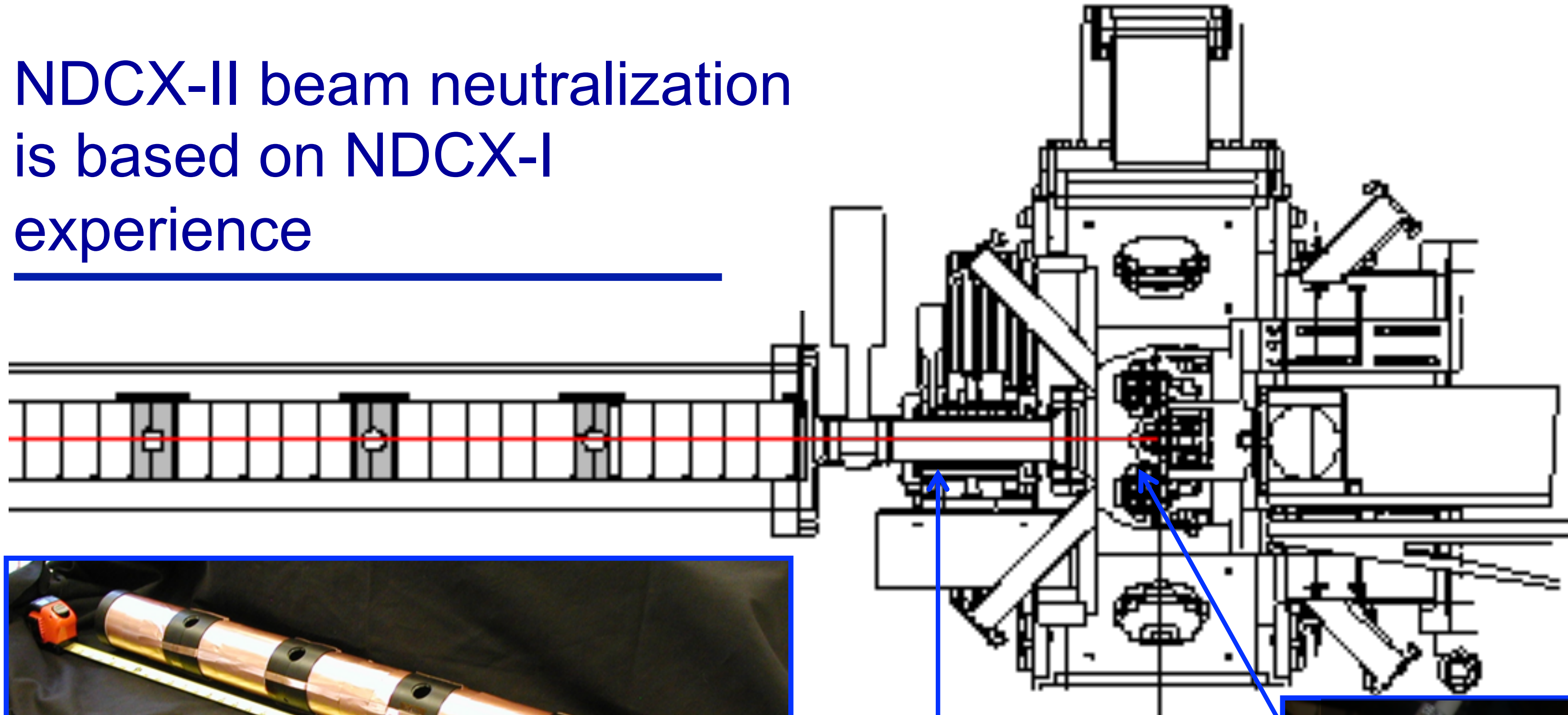


Final Focus and Target chamber

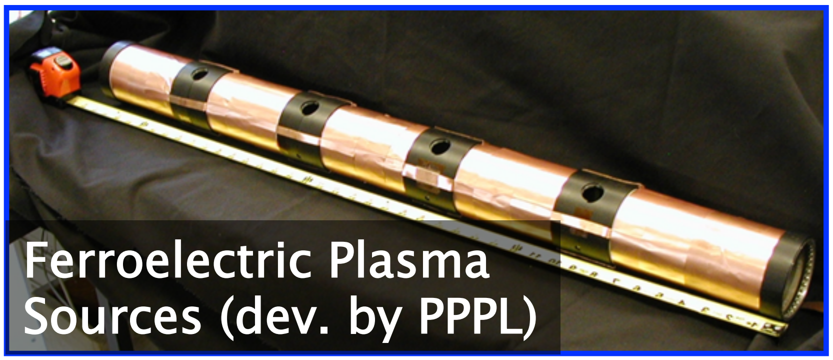
Neutralized Drift Compression Section made of Ferroelectric Plasma Sources

Solenoid for transverse confinement of ion beam

NDCX-II beam neutralization is based on NDCX-I experience

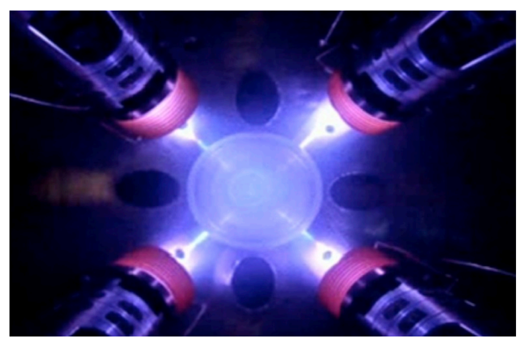


Final-Focus Solenoid (FFS)

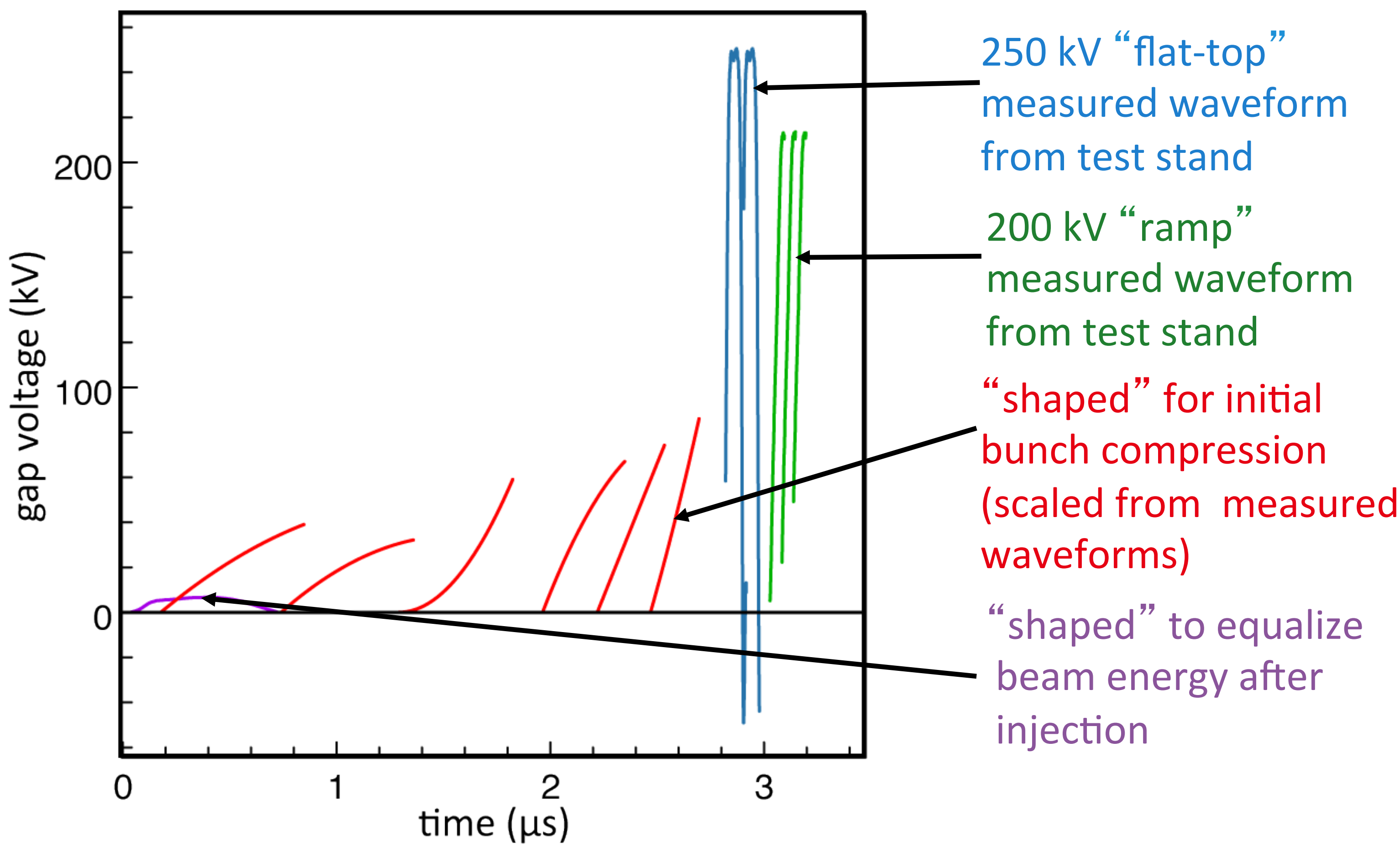


Ferroelectric Plasma Sources (dev. by PPPL)

4 Cathodic-Arc Plasma Sources



Accelerating waveforms are either long-pulse moderate-voltage or short-pulse high-voltage (Blumleins)



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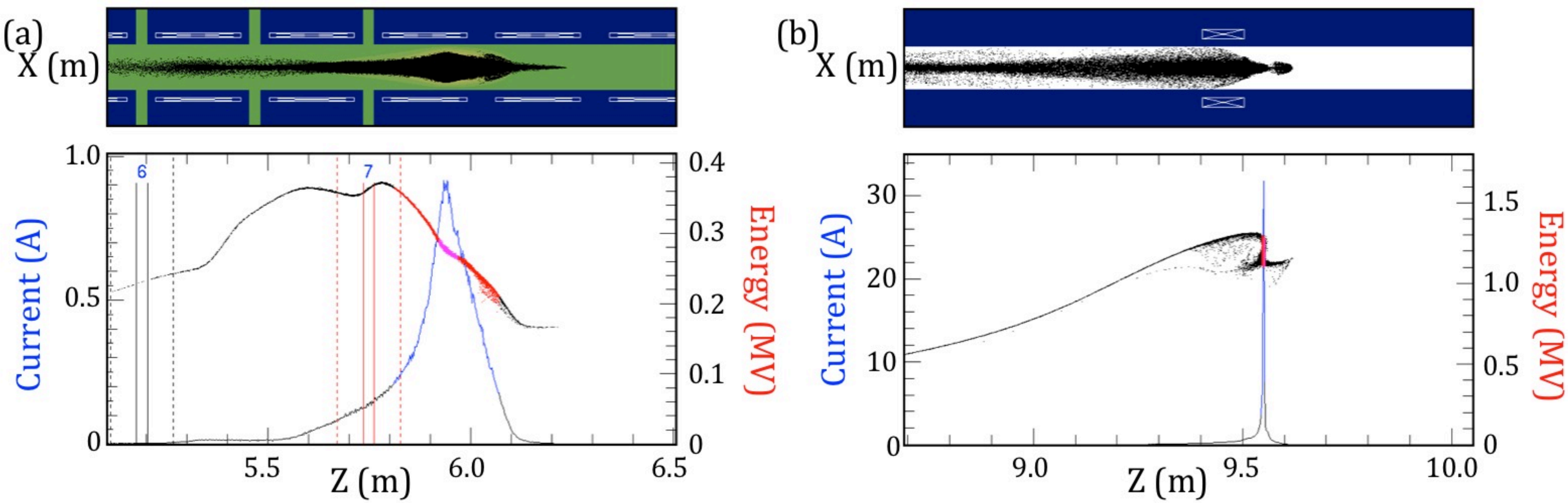
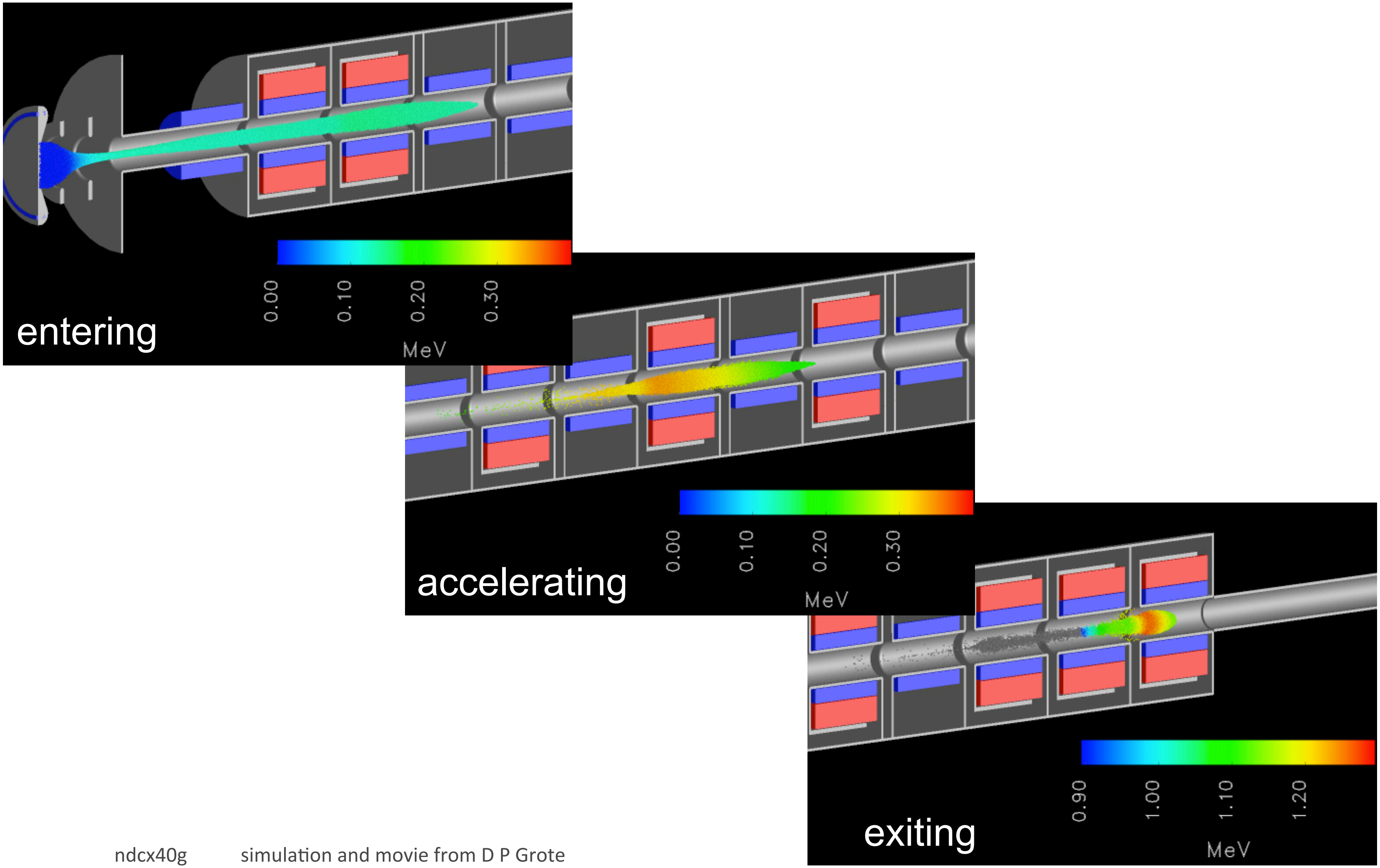
Ion beams are plasmas; strong space charge forces and plasma effects require kinetic simulations along with experiments

R,Z Warp simulation (a) during initial non-neutral compression in accelerator and (b) at peak compression in the target plane.

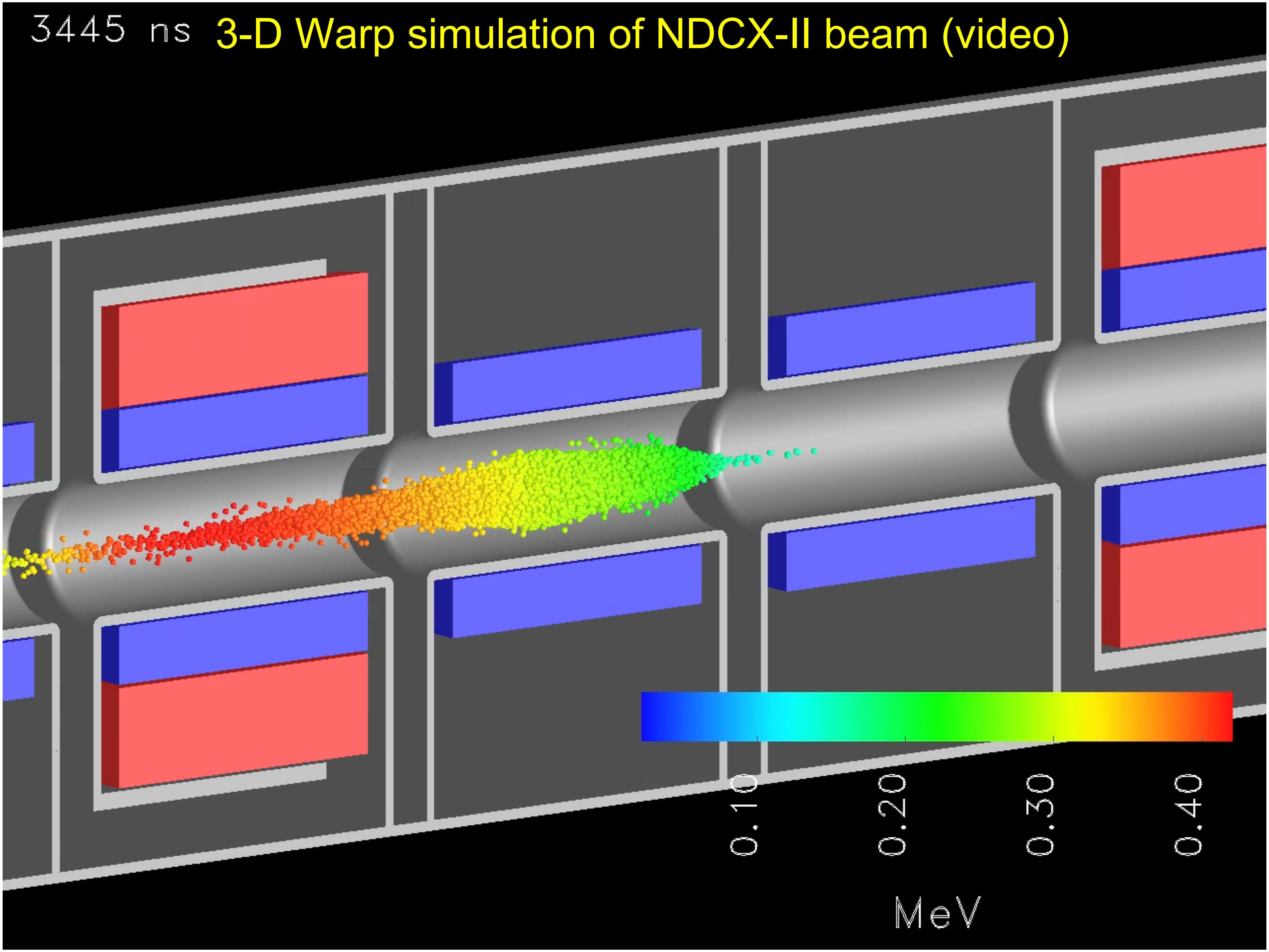


(The low-density tail appears dense due to the large number of simulation particles, but almost all beam is in the red-colored core.)

3-D Warp simulation of beam in the NDCX-II linac



ndcx40g simulation and movie from D P Grote


3445 ns
3-D Warp simulation of NDCX-II beam (video)
0.10
0.20
0.30
0.40
MeV

We use target pressure as the figure of merit for machine optimization

We use a parametric fit to Hydra results for the pressure (in Mbar) that the beam generates in a nominal Al foil target

$$\tau_0 = (0.42 - 0.004 f)(E/2.8)$$

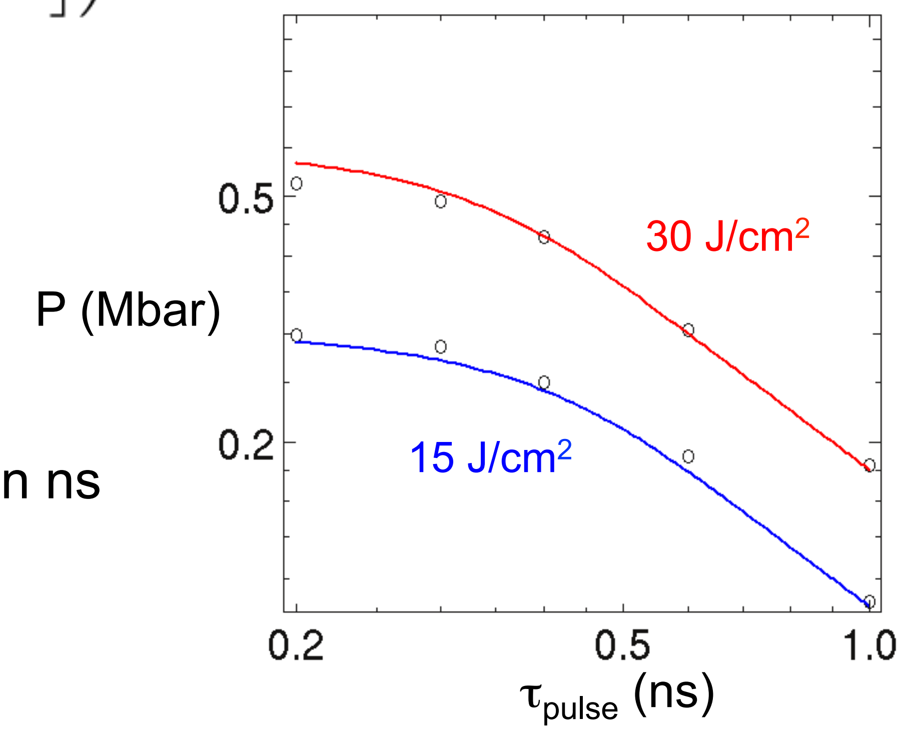
$$P = 0.02 f \left(\frac{2.8}{E}\right)\left(\frac{\tau_0}{\tau}\right)\left(1 - \exp\left[\left(\frac{\tau}{\tau_0}\right)^3\right]\right)^{\frac{1}{3}}$$

Here, f is the fluence in J/cm^2,

τ is the FWHM pulse duration in ns,

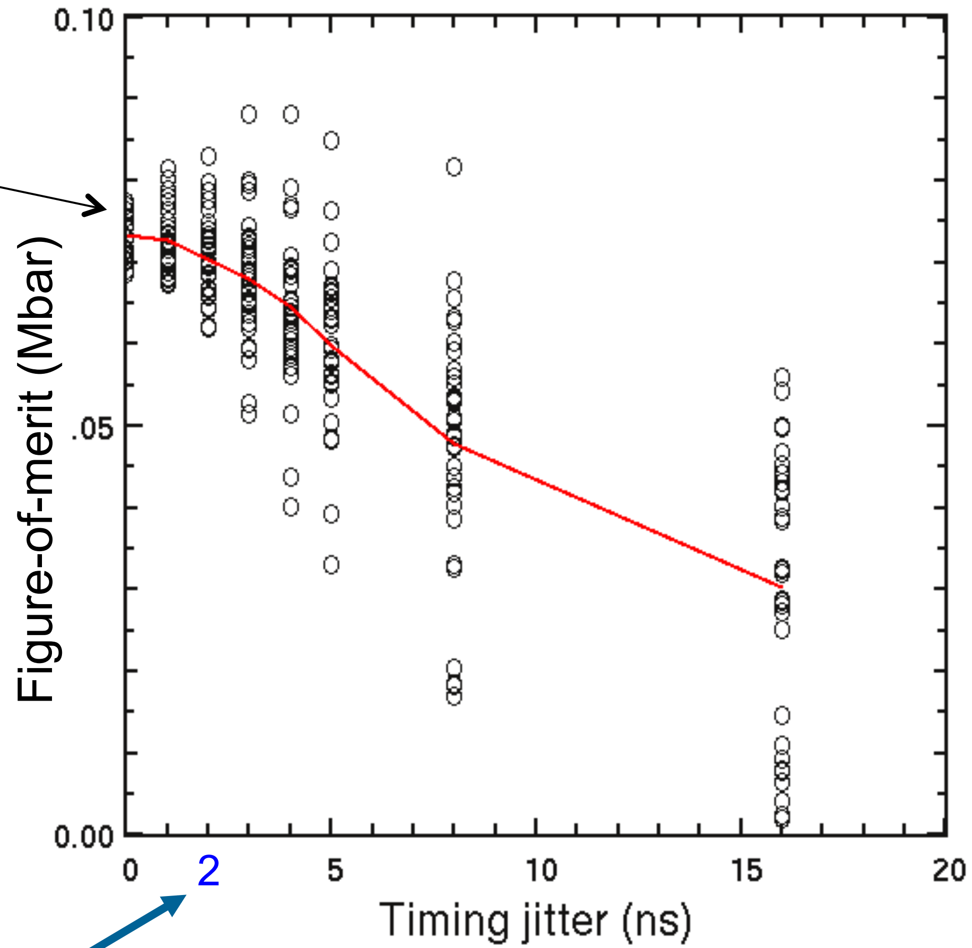
E is the ion kinetic energy in MeV

τ_0 roughly approximates a scale time in ns



We assessed sensitivity to various errors using "ensemble" runs

Spread at zero jitter is due to simulation particle statistics



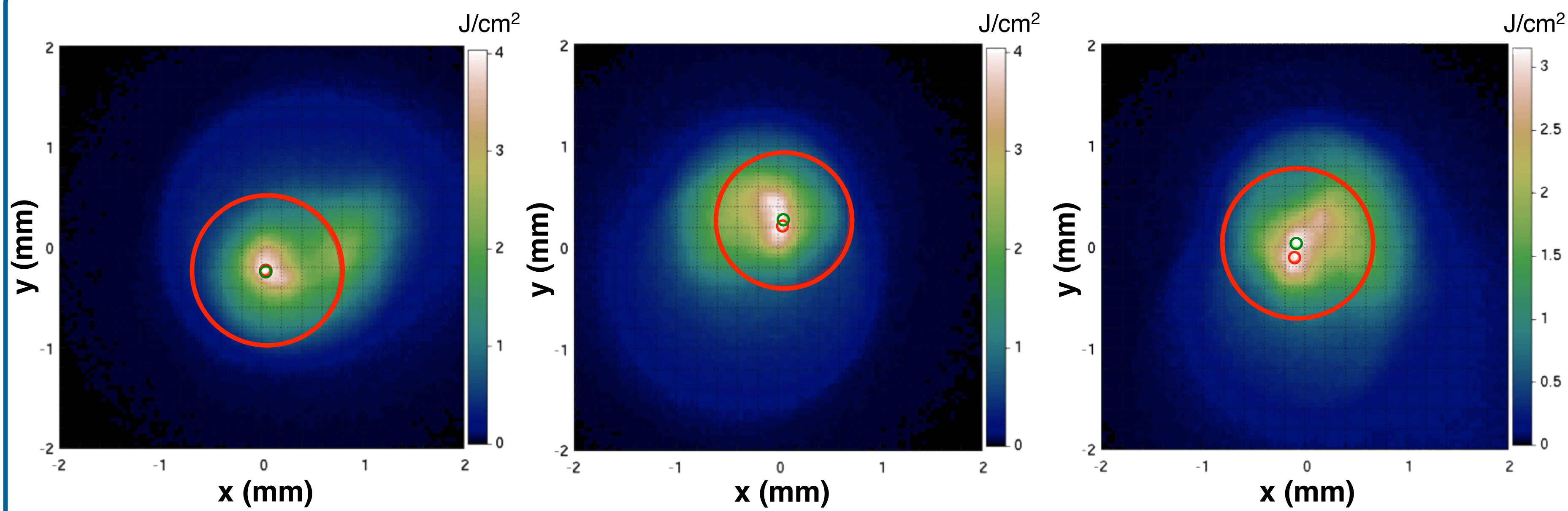
2-ns nominal jitter in firing of acceleration pulses

40g-12

Warp runs showed that a bright spot is achieved with expected machine alignment errors (not expected to vary shot-to-shot)

plots show beam deposition for three sets of solenoid offsets (no steering applied)

- maximum offset for each case is 0.5 mm
- larger red circles include half of deposited energy
- smaller red circles indicate hot spots



ASP and Warp runs show that "steering" with dipoles can increase intensity

see Y-J Chen, et al., Nucl. Inst. Meth. in Phys. Res. A 292, 455 (1990)

NDCX-II capabilities for supporting experiments will grow

- Currently connecting the Blumleins; drift line, final focus, and target chamber will follow
- We will continue to optimize:
  - brightness and uniformity of the injected beam
  - longitudinal beam manipulations and compression
  - beam steering to correct for residual misalignments
  - beam neutralization and final focusing
- The following are goals for the 12-cell configuration

	Now (no Blumleins, drift, focus)	Near term	Longer term
Charge (in $\sqrt{2}$ x duration)	50 nC	25 nC	50 nC
Ion kinetic energy (MeV)	0.2 MeV	1.2 MeV	1.2 MeV
Focal radius (50% of beam)	N/A	1.5 mm	<1 mm
FWHM Duration	50 ns	1.0 ns	<1 ns
Peak current	0.65 A	5 A	>30 A
Peak fluence	N/A	>1 J/cm^2	>8 J/cm^2

Additional induction cells will significantly enhance performance

- Higher kinetic energy, shorter pulse
- Thus higher target pressures, above many critical points
- More uniform heating (beam slows through Bragg peak while in target)

- For 3 MeV, append 10 lattice periods (we have additional cells from LLNL on hand)

	NDCX-I (bunched beam)	NDCX-II	
		12 active cell (27 periods)	21 active cell (37 periods)
Ion species	K^+ (A=39)	Li^+ (A=7)	Li^+ (A=7)
Charge	15 nC	50 nC	50 nC
Ion kinetic energy	**0.3 MeV**	**1.2 MeV**	**3.1 MeV**
Focal radius (50% of beam)	**2 mm**	**0.6 mm**	**0.6 mm**
Duration (FWHM)	**2 ns**	**0.6 ns**	**0.3 ns**
Peak current	**3 A**	**36 A**	**86 A**
Peak fluence (time integrated)	0.03 J/cm^2	8.6 J/cm^2	22 J/cm^2
Fluence w/in 0.1 mm diameter, w/in duration		5.3 J/cm^2	15 J/cm^2
Max. central pressure in Al target		0.07 Mbar	0.23 Mbar
Max. central pressure in Au target		0.18 Mbar	0.64 Mbar

NDCX-II will be a unique user facility for warm dense matter, IFE target physics, and intense-beam physics.